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(54) **METHODS AND MEANS FOR REDUCING TEMPERATURE-INDUCED VARIATIONS IN LENSES AND LENS DEVICES**

VERFAHREN UND MITTEL ZUR VERRINGERUNG VON TEMPERATURBEDINGTEN SCHWANKUNGEN IN LINSEN UND LINSENANORDNUNGEN

PROCEDES ET MOYENS POUR REDUIRE DES VARIATIONS INDUITES PAR LA TEMPERATURE DANS DES LENTILLES ET DES DISPOSITIFS A LENTILLE

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Description

BACKGROUND OF THE INVENTION

This invention relates primarily to lenses composed of a single material and to systems employing such lenses. More particularly, it relates to designs for such lenses which, when used singly or as part of a system, have the property that certain of their optical characteristics remain relatively unchanged with changes in temperature or change in a controlled predetermined way.

Correction of lens aberrations normally requires the use of multiple component lenses even when thermal effects are not a dominant factor. However, there have been some simple designs reported for use over modest temperature ranges where just portions of a single element lens can correct a specific aberration. For example, chromatic aberrations have been corrected by using a single element lens with a conventional refractive or "bulk" portion, and a shallow surface diffractive portion. Here, the diffractive portion reduces the chromatic aberrations introduced by the bulk portion. (W.C. Sweatt, Applied Optics, Vol. 16, No. 5, May (1977).

However, if thermal effects cannot be ignored because they affect performance due to unacceptable changes due to thermal changes in material or geometric properties of a lens, designs for compensating for them i.e., athermalized designs can of necessity become quite complicated. For example, plastic and glass optical materials may change enough so that corresponding changes in focal length or the state of correction of a lens can become intolerable. This is so in part because these materials, especially plastic exhibit large changes in refractive index with temperature changes.

Designers have made lens systems less sensitive to these temperature effects by exploiting the differences in which changes in refractive index or geometry occur in one or more elements to compensate for those introduced by others. This approach, when properly implemented, can result in a thermally balanced arrangement. For example, if it were important to maintain back focal length in a multiple component lens constant over a given temperature, a designer could adjust the properties of individual elements of the lens in such a way the thermally induced increases to back focal length were balanced or offset by the decreases in others. This could be done by control of the thermal properties of lens element geometry or index, or both.

Such compensation may be important, for example, in arrangements used to focus laser beams onto the surfaces of compact disks.

An aspherical optical lens incorporating a kinoform for correcting spherical aberration of spherical glass lenses is known from JP-A-4-016 910. The kinoform therein is formed on the spherical glass lens by separately applying a coat of an optically transparent resin to one of the lens surfaces and thus requires a multi-step manufacturing process.

While such a solution suffices for lenses having multiple components, it is unsuitable for systems using a single lens element made of one material. Hence, there continues to be a need for simple and uncomplicated lens elements or components by which thermal effects can be usefully controlled, and it is a primary object of this invention to provide such.

Another object of the invention is to provide a single-material lens with selected optical characteristics that vary with temperature in a selected manner, for example, in a manner which maintains an optical characteristic substantially constant at a given wavelength.

Another object is to supply an athermalized single-material lens with substantially constant focal length, spherical aberration correction, or any combination of these.

The above objects are achieved by the combined features of claim 1.

Yet another object of the invention is to provide a single-material lens that compensates not only for temperature-induced optical variations of the lens itself but also the temperature-induced variations in the structure spacing the lens from an object or a sensor at or near a specific dominant wavelength.

The above object is achieved by the combined features of claim 9.

The invention also concerns a method of manufacturing a lens according to claim 12.

Other objects and advantages of the invention will become evident from the following detailed description when read in light of the accompanying drawings.

The invention is based upon the recognition that a kinoform produces a temperature-induced optical response different from that of the bulk material in which it may be formed and that the kinoform's temperature-induced optical response can be used opposition to that of a refractive lens formed of the bulk material, even in cases where kinoform is itself formed of the same material.

According to a feature of the invention, a lens comprised of a single optical material has a refractive or bulk portion having a given optical characteristic at one dominant wavelength that shifts in one sense in response to a temperature change and includes a "kinoform", or diffractive portion that responds to the same temperature change at the same wavelength by shifting the lens characteristics in a sense opposite to that of the bulk portion and in a predetermined selected manner.

According to another feature of the invention, the kinoform shifts the lens characteristic in an amount sufficient to compensate for the temperature change in the bulk portion.

According to another feature of the invention, the lens forms part of a lens arrangement which includes spacers for spacing it from a target such as an object or a film, and the kinoform compensation offsets not only the temperature induced shifts in the bulk portion but in the spacing as well.

According to yet another feature of the invention, the compensation counteracts the effect of temperature changes in back focal length at a dominant wavelength; and, according to yet another feature, it offsets the effects of temperature changes on spherical aberrations.

According to yet another property of the invention, the kinoform power is normally greater than the bulk refractive power.

The foregoing and other features of the invention are particularly set forth in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The principles of the present invention may be clearly understood by considering the following detailed description in conjunction with the accompanying drawings in which:

Figure 1 is a diagrammatic cross-section of a thin lens embodying features of the invention;
Figure 2 is diagrammatic rear view of the lens in Figure 1;
Figure 3 is an enlarged diagrammatic view of part of some of the features of the lens of Figure 1;
Figure 4 is a diagrammatic, cross-section of a thin convex - plano lens of the invention;
Figure 5 is a diagrammatic, cross-sectional view of a device embodying features of the invention;
Figure 6 is a diagrammatic perspective view of another lens embodying features of the invention;
Figure 7 is a diagrammatic, cross-sectional view of another lens embodying features of the invention;
Figure 8 is a diagrammatic view of a special lens as an example for athermalizing any selected order of spherical aberration;
Figure 9 is a diagrammatic view used to illustrate certain mathematical relationships helpful in understanding the invention;
Figures 10 is a cross sectional view of another lens embodying features of the invention;
Figure 11 is a diagrammatic view of an inventive lens fabricated of PMMA using diamond turning techniques;
Figure 12 is a perspective photograph of the lens of Fig. 11; and
Figure 13 is a graph showing the performance of the lens of Fig. 11 with temperature.

DESCRIPTION OF PREFERRED EMBODIMENTS

Figures 1 and 2 illustrate a hybrid lens 10 composed of a single plastic material. According to one embodiment of the invention, the material is a plastic known as polymethylmethacrylate (PMMA). Lens 10 comprises a negative refractive surface 14 on one side and a generally convex composite surface which one may consider as composed of a base positive refractive surface 16 and a kinoform 20. Kinoform 20 includes annular grooves, 22 having typical outer profiles 24 and inner rises 26. The underlying base shown as surface 16 extends along the valleys of annular grooves 22.

The profiles 24 form angles γ measured from a line parallel to surface 16 at the apex of each groove 22 as shown in Figure 3. The underlying refractive surface 16 and the refractive surface 14, together with the material between them define a bulk refractive lens or lens portion. Depending on the refractive index of the material, this lens portion exhibits a bulk power, ϕ_B, quite apart from kinoform 20. The distances between adjacent valleys or peaks in the kinoform 20 determine the power of the kinoform. The profiles 24 are shaped to maximize the amount of light that goes into a selected diffraction order of kinoform 20. Obviously, it will be appreciated that the scale of the feature of lens 10, and others shown subsequently, have been greatly exaggerated for clarity in illustrating principles.

As is well-known, a kinoform is a diffractive wavefront reconstruction device as described, for example, by L.B. Lesem, P.M. Hirsch, and J.A. Jordan, Jr. in the IBM Journal of Research Development, pp 150-155, (1969). Kinoforms may be considered as phase matched Fresnel lenses with phase steps of $2K\pi$ where K is an integer designating the diffraction order, i.e., the height of rise 26. As such, they combine properties of a classic Fresnel lens, O.E. Miller, J. H. McLeod and W.T. Sherwood, "Thin Sheet Plastic Frensel Lenses of High Aperture", (JOSA Vol, No. 1, pp 807-815, Nov. 1951) with those of a classic Fresnel zone plate Robert W. Wood, Physical Optics, Third Edition (1934), Optical Society of America Reprint, pp 32-39; pp 252-254 (1988). As used herein, the term refers to phase-only surface-relief lenses that can be made to be nearly 100% efficient for a given wavelength and order by designing the geometry of each groove through choice of the shape and depth of each peak and valley, neglecting absorption.

Temperature induced changes in the optical characteristics, for example, in this case back focal length at a given

wavelength, of the bulk portion lens 10 occur at a rate different from changes in the same characteristics, over the same temperature changes, in kinoform 20. Moreover, in PMMA lens 10, kinoform 20 exhibits temperature induced focal length changes of a sign opposite to that of the refractive bulk portion.

Together the bulk lens, with its refractive surface 14 and surface 16, and the kinoform 20 focus collimated rays of light 38 onto a focal point 40 at a back focal length 42 from the vertex of the kinoform 20, shown designated at 44. Thermally induced changes in the index of refraction and the geometry of the bulk lens bounded by the refractive surfaces 14 and 16 would ordinarily change back focal length 42 of lens 10 for any predetermined wavelength, such as 815 nm. In Figures 1 and 2, kinoform 20 offsets such temperature-induced changes in the index of refraction and the geometry of the bulk lens for a predetermined wavelength. This results in a substantially temperature-independent, i.e., athermalized, back focus for lens 10 at the predetermined wavelength. The athermalization may occur exactly at chosen temperatures and vary slightly between the temperatures. On a practical basis, one can consider it as covering a given temperature range.

The material of lens 10, including the bulk lens and kinoform 20 is a continuous material, i.e., PMMA. Available handbooks, such as the Photonics Handbook, published in 1991 (T.C. Laurin, Pittsfield, MA) pages H-302 and H-304, contain information about the material response to temperature. The same handbook permits determination of the power of kinoform 20, and one can select the kinoform power to be opposite in sign from the power of the underlying bulk lens. The total power of the lens 10, considered as a thin lens, is equal to the power ϕ_B of the bulk lens plus the power ϕ_K of kinoform 20. Thus:

$$\Phi_T = \Phi_B + \Phi_K \tag{1}$$

In the ideal athermalized lens 10 the total temperature induced change $d\phi_T/dt$ equals 0. Hence,

$$\frac{d\Phi_T}{dt} = \frac{d\Phi_B}{dt} + \frac{d\Phi_K}{dt} = 0 \tag{2}$$

On a practical basis, $d\phi_B/dt$ is substantially equal to $-d\phi_K/dt$ in the athermalized lens at the predetermined wavelength, such as 815 nm, over a given temperature range.

Making the hybrid lens 10 of Figures 1 and 2 so it substantially reduces the change in focal length or other optical properties with temperature involves, collectively, optimizing the shapes of surfaces 14 and 16 of the bulk lens, determining the temperature induced change in power of the bulk lens as a refractive element, and also defining the structure of kinoform so that its temperature induced change in power is equal in magnitude but opposite in sign to that of the refractive bulk lens. In this manner, these properties of hybrid lens 10 remain substantially constant at a given wavelength as its temperature varies over a selected range. In other words, as the power of the bulk lens increases or decreases with temperature, the power of kinoform 20 varies in the opposite direction to substantially counterbalance the effect of temperature induced changes of the bulk lens.

An expression for the change on index of refraction with temperature as it relates to the coefficient of linear expansion can be obained as follows:

$$D = \frac{m}{L^3} = C\,\frac{n^2-1}{n^2+2} \tag{3}$$

This relationship is known as the Lorentz-Lorenz relationship (Roy M. Waxler, Deane Horowitz, and Abbert Feldman, "Optical and Physical Parameters of Pleixglas 55 and Lexan", Applied Optics, Vol. 18, No. 1, p 101, Jan., (1989).
where

D is the density of the PMMA material,
m is the mass,
L is length.
C is a constant of proportionality.
n is the refractive index.

The material expands or contracts to a length L from a length L_o as follows:

$$L = L_o (1 + \alpha \Delta t) \quad (4)$$

where α is the linear coefficient of expansion, and Δt is the temperature change.
Then:

$$\frac{dL}{dt} = L_o \alpha \quad (5)$$

By using Equation (5) and differentiating Equation (3) we get:

$$\frac{dn}{dt} = \frac{-\alpha (n^2-1)(n^2+2)}{2n} \quad (6)$$

For a value of n = 1.49, this gives a value -1.73 α for dn/dt.

At the same time the approximate bulk power of a thin plano-convex or planar concave lens is:

$$\Phi_B = \frac{1}{f} = \frac{n-1}{r} \quad (7)$$

As in Equation (4), $r = r_o (1 + \alpha \Delta t)$.
Differentiating the value of ϕ_B we get

$$\frac{d\Phi_B}{dt} = \frac{n-1}{r^2} \frac{dr}{dt} + \frac{1}{r} \frac{dn}{dt} \quad (8)$$

$$\frac{1}{\Phi_B} \frac{d\Phi_B}{dt} = -\frac{1}{r} \frac{dr}{dt} + \frac{1}{(n-1)} \frac{dn}{dt} \quad (9)$$

Substituting for dn/dt results in the change in bulk power relative to an original bulk power

$$\frac{1}{\Phi_B} \frac{d\Phi_B}{dt} = -\alpha \left[\frac{2n+(n+1)(n^2+2)}{2n}\right] \quad (10)$$

As a first order approximation, kinoform 20 varies in focal length $f = a^2/\lambda$, where a is the semidiameter of the first diffraction zone and λ the wavelength in question. Hence $\phi_K = \lambda/a^2$. If we differentiate to obtain the temperature induced change and then divide by ϕ_K to show the change relative to a given power, we get

$$\frac{1}{\Phi_K} \frac{d\Phi_K}{dt} = -2\alpha \quad (11)$$

If the total power change $d\phi_T/dt$ is to be 0,

$$\frac{d\Phi_T}{dt} = \frac{d\Phi_B}{dt} + \frac{d\Phi_K}{dt} = O \quad (12)$$

$$\frac{d\Phi_T}{dt} = -\alpha\left[\frac{2n + (n-1)(n^2+2)}{2n}\right]\Phi_B - 2\ \alpha\ \Phi_K = O \qquad (13)$$

So ϕ_T will be constant with temperature when:

$$\frac{\Phi_K}{\Phi_B} = -\left[\frac{2n + (n+1)\ (n^2-2)}{4n}\right] \qquad (14)$$

With a refractive index of 1.49, the ratio of kinoform power to bulk power is -2.263, an approximate result derived from fundamental principles.

These equations permit first order approximation of ϕ_B and ϕ_K for a desired valued ϕ_T.

A more accurate determination is available from handbook computation, using

$$\frac{dn}{dt} = -11.5\times10^{-5}\ \textit{per degree C} \qquad (15)$$

The focal length of the bulk portion of a thin concave plano lens 30 as shown in Fig. 4 is $f_B = r/(n-1)$ where r is the effective radius of its front surface 32 and 33 is its kinoform. Starting from a value $r = r_0$ and an index $n = n_0 = 1.49$, the changed focal length in the bulk lens portion for each degree change in centigrade of the lens 30, assuming again PMMA lens is:

$$f_B = \frac{r}{(n-1)} = \frac{r_o(1+\alpha\Delta t)}{n_o + dn/dt\ \Delta t - 1} = \frac{r_0(1+(6.74\times10^{-5}\Delta t))}{(n_0-11.5\times10^{-5}\Delta t)-1} = \qquad (16)$$

$$\frac{r_o}{(n_o-1)}\ \frac{1+6.74x10^{-5}\ \Delta\ t}{1-23.47x10^{-5}\ \Delta\ t} = \frac{r_0}{n_o-1}\ (1+30.21x10^{-5}\ \Delta\ t) \qquad (17)$$

The equation that expresses the relationship for the temperature related changed focal length per degree centigrade in kinoform 33 is:

$$f_K = \frac{a^2}{\lambda} = \frac{a_o^2(1+\alpha\Delta t)^2}{\lambda} = \frac{a_o^2(1+6.74x10^{-5}\Delta t)^2}{\lambda} = \frac{a_o^2}{\lambda}[1+13.48x10^{-5}\Delta t] \qquad (18)$$

The ratio of the bulk lens power change rate to that of the kinoform power change rate, after solving the above equations, is:

$$-\frac{30.21\ x\ 10^{-5}}{13.48\ x\ 10^{-5}} = -2.241 \qquad (19)$$

This result, based on published measured properties of PMMA, is in excellent agreement with equation (14), from fundamental electromagnetic properties of matter. There are other materials, however, such as glasses, for which dn/dt does not follow the Lorentz-Lorenz relation. For them, measured values must, of course, be used.

Another embodiment of the invention involves measuring the values of temperature induced changes and constructing the inventive lens on the basis of the measurements on the material and the lens. A combination of calculations and measurements also serves this purpose.

In thin lens 30, using PMMA as the lens material, with handbook values to determine the bulk power for both the bulk lens portion and for the kinoform portion, the ratio of percentage change in the bulk power to that of the kinoform is 2.24 as stated previously. All phase steps in the kinoform 33 are 2π, since the design diffractive order is 1. Thus, the power of the bulk lens changes at a rate 2.24 times as fast as does the percentage power of the kinoform portion as the temperature of the material increases, and in a direction opposite to that of the kinoform portion. For example, if the bulk lens portion has a power of -.806 diopter, and the kinoform portion has a power of +1.806 diopter, the sum of the two is +1.00 diopter. With a change of 1° C, the bulk lens portion will weaken by 2.24 times the rate at which the kinoform power weakens. Because of the substantially linear relationship between the rate of change of the bulk power and the kinoform power, the net power change across entire lens element 30 at different temperatures will be substantially zero, at least as a first approximation. Accordingly, the back focal length of lens element 30 tends to remain substantially constant despite the variation in temperature which it may experience.

According to another embodiment of the invention, the kinoform power reduces the response of the inventive lens to changes in temperature without totally athermalizing the lens. That is, the kinoform does not offset the temperature-induced variations entirely, but only to achieve a predetermined effect, i.e.,

$$d\frac{\phi_B}{dt} + d\,\frac{\phi_K}{dk} \neq o$$

Consequently, the invention is applicable not only for athermalizing a lens alone, but an entire device, which includes the inventive lens and other elements such as a spacer which may be used for locating the lens with respect to a focal plane, film, or detector. An embodiment like this appears in Figure 5. Here, a spacer 50 spaces a lens 52 from a plane 54, which may be a film or detector. The spacer 50 constitutes a lens mount or other structure that supports the lens relative to the plane 54. The lens 52 includes a refractive surface 56, a kinoform 60, and a bulk portion again formed by the refractive surface 56 and a base surface 58 in which kinoform 60 resides. The spacer 50 exhibits a temperature induced change in dimensions which varies the spacing 62 between lens 52 and plane 54. The structure of lens 52 is similar to that of lens 10. However, here the relationship between the bulk power ϕ_B and the kinoform power ϕ_K serves not only to correct temperature induced changes within the lens 52, but also, for temperature induced dimensional changes in the spacer 50.

The kinoform 60 and bulk lens portion of lens 52 have structures to maintain the focus of the lens 52 constant over a given temperature range at a predetermined wavelength despite thermally induced changes in lens 52 and in the spacer 50. Specifically, kinoform 60 does not compensate only for the temperature induced changes of the bulk portion. Rather, kinoform 60 departs from lens athermalization alone and compensates for both temperature-induced bulk power changes and temperature-induced changes in the linear dimension of spacer 50, enough to keep the focus of the lens on the plane 52. Where S_S is the dimension of the spacer, the following conditions prevail:

$$\frac{d(FL)}{dt} = \frac{d}{dt}\left(\frac{1}{\phi_B + \phi_K}\right) = \frac{dS_s}{dt} \tag{21}$$

An embodiment of the invention using a cylindrical lens appears in Figure 6. Here, the material, values of ϕ_B, ϕ_K, and n are the same as the values for ϕ_B, ϕ_K, n_0 in Figures 1 and 2. Figure 6 depicts a cylindrical lens element 70. The cylindrical lens 70 focuses on a line and corrects for temperature induced focal length changes in the same manner as the examples of Figures 1 and 2. Lens 70 of Figure 6 has its kinoform grooves running parallel to axis 72. The focal length of these cylindrical lenses likewise can be made to remain substantially constant as temperature varies.

According to another embodiment of the invention, spacer 50 spaces the lens 70 from the focal plane 54. That is, the lens 70 replaces the lens 52 in Figure 5. The same power conditions as in the lens of Figures 1 and 2 prevail.

Another more detailed embodiment of the invention appears in Figure 7. Here a hybrid or composite lens 80 corrects not only for temperature induced back focal length changes but for image quality by controlling the aberrations in the image by using an aspheric front surface 86 for the refractive surface, and kinoform grooves 82. Hybrid lens 80 works well at a wavelength of 815 nm, is an F/2 lens, has a normal back focal length (BFL) of f = 5mm and exhibits diffraction limited performance over a field of view of 1° for a temperature range of 0°C to 40°C, for the first order. At 0°C the BFL is 5.0 mm, at 20°C the BFL is 4.993, and at 40°C it is 5.0 mm. Thus, this lens is a thermal to less than 1 part in 10[illegible]. Details of the lens 80 in Figure 7 were obtained by first modeling lens 80 with an equivalent refractive lens having the following constructional data with the kinoform represented by a fictitious high index layer defined on one side by a sphere and on the other by an asphere.

CURVATURE	THICKNESS	INDEX	MATERIAL
OBJ : 0.000000 1: - 0.30724044	INFINITY 0.50000	1.495400 PLEXI	PLEXI
ASPHERIC:			
K: 0.00000 IC: YES A: 0.956778E-02 AC: 0 BC:0 2: 0.11126357 STOP: 0.11122365	KC: 100 CUF: 0.0000 B: 0.750010E-03 CC: 100 0.0 5.006346	CCF: 100 C: 0.00E+0 DC: 100 10001	D: 0.00E+00
ASPHERIC:			
K: 0.0 KC: 100 IC: YES A: 0.417578E-06 AC: 0 BC: 100 IMG: 0.00000	CUF: 0.0 B: 0.0 CC: 100 0.00000	CCF: 100 C: 0.0 DC: 100 100	D: 0.0 100

where:

Dimensions are in mm;
Wavelength is 815 mm;
OBJ stands for "Object";
and the aspheric sag profile is given by:

$$Z(y) = \frac{(CV)y^2}{1+\sqrt{1-(1+K)(CV)^2y^2}} + ay^4+by^6+cy^8+dy^{10} \qquad (22)$$

K stands for the conic constant;
a, b, c, d are aspheric coefficients
(CV) is the base curvature

INFINITE CONJUGATES	T =0_0C	T = 20°C	T = 40°C
EFL	4.7579	4.7578	4.7592
BFL	5.0000	4.9993	5.0000
FFL	-4.2097	-4.2094	-4.2103
FNO	1.9031	1.9031	1.9037
IMG DIS	5.0000	4.9991	5.0000
CAL	0.4994	0.5000	0.5007
PARAXIAL IMAGE			
HT	0.0830	0.0830	0.0831
ANG	1.0000	1.0000	1.0000

(continued)

INFINITE CONJUGATES	T =0°C	T = 20°C	T = 40°C
ENTRANCE PUPIL			
DIA	2.5000	2.5000	2.5000
THI	0.3178	0.3186	0.3196
EXIT PUPIL			
DIA	2.6272	2.6269	2.6265
THI	0.0000	0.0000	0.0000
STO DIA WAV	2.6766	2.6762	2.6756

In lens 80 of Figure 7, kinoform grooves 82 have respective radii or semi-diameters y which are extracted from the equivalent refractive model, i.e., a groove exists at each position where the optical path difference (OPD) introduced by the kinoform structure equals a multiple of the wavelength λ for the first order. That is, a groove 82 occurs when:

$$OPD(y)=Ki\lambda \qquad (23)$$

where i = 1,2,3,4,5.... number of zones.

Here, the diffractive nature of a kinoform was simulated by the Sweatt model (W.C. Sweatt, J. Opt. Soc. Am., 67 804 (1977) and J. Opt. Soc. Am., 69, 486 (1979)). In this model, a kinoform is represented by a thin lens of central thickness zero and a very large index of refraction. An index of 10,001 was appropriate for this example. The surfaces of the equivalent lens can be aspheres of the form $Z = a_m r^{m+1}$ as needed (See Fig. 7) to correct for aberrations.

The OPD (optical path difference) introduced by the kinoform 84, i.e., the collection of grooves 82, is in general:

$$OPD = (n_{high}-1)\,(Z_2 - Z_1)\cos(\tan^{-1}\varepsilon) \qquad (24)$$

where ε is the interior angle made by the ray in question with respect to the optical axis in the high index equivalent lens.

The following equation provides the value Z.

$$Z_{asphere} = \frac{(CV)}{2}y^2 + Gy^4 + Hy^6 + Iy^8 + Jy^{10} \qquad (25)$$

Where CV = the vertex curvature of an asphere, and where:

$$G=a+\left[\frac{(1+K)}{8}\right](CV)^3 \qquad (26)$$

$$H = b + \left[\frac{(1+K)^2}{16}\right](CV)^5 \tag{27}$$

$$I = c + \left[\frac{5(1+K)^3}{128}\right](CV)^7 \tag{28}$$

$$J = d + \left[\frac{7(1+K)^4}{256}\right](CV)^9 \tag{29}$$

Where K = conic constant; and
a, b, c, d are aspheric departures.
Continuing:

$$\cos(\tan^{-1}\epsilon) = 1 - \left[\frac{(CV)^2}{2}\right]y^2 + \left[\frac{(CV)^4}{24} - 4(CV)G + \frac{(CV)^4}{3}\right]y^4 + \tag{30}$$

$$\left[6(CV)^3G - 6(CV)H - \frac{5(CV)^6}{16} - 8G^2\right]y^6 + \tag{31}$$

$$y^8\left[9(CV)^3H + 36(CV)^2G^2 - \frac{15(CV)^5G}{2} - 24GH - 8(CV)I + \frac{35(CV)^8}{128}\right]. \tag{32}$$

By appropriately substituting equation 23 to 30 into equation 22 we obtain values of y when the OPD = $i\lambda$.

The following table shows the values of y for the first five and last five zones or grooves 82 where the wavelength λ is 815 nm.

Zone #	y (mm)	Zone size (mm)	Zone size (wavelengths)
1	0.063902	0.026472	32.481

(continued)

Zone #	y (mm)	Zone size (mm)	Zone size (wavelengths)
2	0.090374	0.020316	24.927
3	0.110690	0.017128	21.016
4	0.127818	0.015092	18.318
5	0.142910		
476	1.242816	0.001735	2.129
477	1.244551	0.001735	2.127
478	1.246284	0.001731	2.124
479	1.248015	0.001729	2.121
480	1.249744		

Hybrid lens 80 corrects not only for back focal length as temperature varies, but also for other aberrations.

In the earliest discussion, a thin lens solution was derived to show that a conventional (bulk) lens can be constructed with a kinoform surface, even made of the same material, to achieve stability of an image position with temperature. The immediately preceding example was more complicated, showing an aspheric refractive surface. The more general care of a thin lens is seen in Figure 8. We now can show that this art will also permit athermalization of spherical aberration contributions of all orders, so that an image will remain fully sharp and well-defined, as well as stationary as temperature changes. The lens of Figure 8 is thin and nearly flat. As a bulk lens it derives its power from the left side, which can be defined in shape by a polynomial expression made up of power terms such as $Z = a_m r^{m+1}$, where Z is the departure of the lens surface from flatness at distance r from its axis, a_m is a constant to be selected, and m is a chosen integer. A weak elementary simple lens is well represented by the parabolic term with m = 1. We can select terms with other values of m, either singly or in combination, to represent arbitrary amounts of spherical aberration, enabling us to make the focal length L of the lens remain exactly constant at any choice of zonal height h, or to cause L to vary as a function of h at any rate desired. For present purpose here we can describe the left surface of the lens with any <u>one</u> of the power terms and will show that it can be athermalized individually by a suitable choice of kinoform on the right side. Any desired general lens can then be described by a summation or superposition of such pairs of bulk power terms and kinoform athermalizing solutions, and such a general lens will be athermalized to any or all orders of spherical aberration.

The kinoform side may be described mathematically in various ways, including a tabulation of the radius of each and every grooved facet. Here we will again use the Sweatt model, in which a kinoform is replaced with a vanishingly thin lens formed of a fictitious material of absurdly high refractive index, in such a way that the mathematically important optical properties of that material approach sufficiently close to the properties of a kinoform. One can think of any tiny sample of the area of a kinoform as identical in functions to a tiny diffraction grating; in the Sweatt model each such elemental diffraction grating is replaced by a tiny wedge prism of increasing refractive index and vanishing angle, matching that diffraction grating in all light-deviation properties. By analogy with the bulk (left) side of our lens, we will describe the kinoform (right) side of our lens by use of the Sweatt model equivalent with shape defined by terms such as $Z = b_m h r^{m+1}$. (It is familiar art to convert such a description together with the fictitious high refractive index, to a tabular listing of all of the grooved facet zonal radii needed for constructing any resulting embodiment.)

At a general ray height, h, a ray of light parallel to the lens axis will encounter a surface $Z = a_m r^{m+1}$ at a depth $Z = a_m h^{m+1}$ beyond a flat surface and strike it at an angle of incidence i given by its slope $i = Z' = (m + 1) a_m h^m$ (See Fig. 9). (Because the lens is weak, we will make no distinction here between the small angles, their tangents, and their sines.) By Snell's law the refracted angle is $\theta = i/n$, within the bulk material of index n. The angle this ray now makes with the axis is $i-\theta = (m+1)(1-1/n)\, a_m h^m$. At the flat right side the ray will encounter the surface at this same angle $(i-\theta)$ of incidence, and by Snell's law again will emerge at the angle:

$$n(i-\theta)=(m+1)(n-1)a_m h^m. \tag{33}$$

Because the lens is very thin, we ignore the small change in height where the ray emerges. Our ray will cross the lens axis at the distance L given by $L=h/n(i-\theta)$, and we may consider this a kind of "focal length" associated with this zonal height, h, and this choice of a_m and m. For convenience in combining the influence of the bulk lens with that of

the kinoform, we will express this as a "power", P_B,

$$P_B = 1/L = n(i-\theta)/h = (m+1)(n-1)a_m h^{m-1}.$$

To evaluate P_B after thermal expansion, we note that

$$Z = a_m[h(1-\alpha\Delta t)]^{m+1} \tag{35}$$

and

$$Z' = (m+1)a_m[h(1-\alpha\Delta t)]^m \tag{36}$$

We note also that $P_B = (n-1)\,Z'/h$.
Therefore,

$$\frac{dP_B}{dt} = \frac{(n-1)}{h}\frac{dZ'}{dt} + Z'\frac{dn}{dt}/h \tag{37}$$

$$= \frac{(n-1)}{h}\, m(m+1)a_m[h(1-\alpha\Delta\, t)]^{m-1}\,(-h\alpha) - \frac{\alpha(n^2-1)(n^2+2)}{2n}\, z'/h \tag{38}$$

(The second term was derived earlier from the Lorentz-Lorenz relation.) And finally this can be simplified to:

$$\frac{dP_B}{dt} = -\,P_B\,\alpha\left[m + \frac{(n+1)(n^2+2)}{2n}\right] \tag{39}$$

On the kinoform side, using the Sweatt representation of the kinoform and high fictitious index N, we have a similar set of calculations. At ray height h, ignoring slight height and slope changes introduced by the thin bulk lens,

$$Z = b_m h^{m+1} \tag{40}$$

$$Z = (m+1)b_m h^m \tag{41}$$

By the same reasoning as before for the other surface,

$$P_K = \frac{(N-1)Z'}{h} = (N-1)(m+1)b_m[h(1-\alpha\,\Delta\, t)]^{m-1} \tag{42}$$

Again,

$$\frac{dP_K}{dt} = \frac{(N-1)}{h}\frac{dZ'}{dt} + \frac{Z'}{h}\frac{dN}{dt} \tag{43}$$

$$= \frac{(N-1)}{h}\, m\,(m+1)\, b_m[h(1-\alpha\,\Delta\, t)]^{m-1}(-h\alpha) \tag{44}$$

$$-\,\frac{(m+1)}{h}\, b_m h^m\,\alpha\, N \tag{45}$$

The second term here is derived not from the Lorentz-Lorenz relation, but from the temperature dependence of the fictitious material of index $N=N_o(1-\alpha \Delta t)$ implicity needed to match the Sweatt model to the thermal expansion rate of α of each elemental diffraction grating expanding at the rate $(1 + \alpha \Delta t)$.

Finally we can simplify the expression to:

$$\frac{dP_K}{dT} = -(m+1)\,\alpha\, P_K \tag{46}$$

So for the mth order of both surfaces, when combined, we have the sum:

$$P = P_B + P_K$$

To athermalize this m^{th} order we require:

$$O=\frac{dP}{dt}=\frac{dP_B}{dt}+\frac{dP_K}{dt}=-\alpha\,\{[m+\frac{(n+1)(n^2+2)}{2n}]P_B=(m+1)P_K \tag{47}$$

Let m = 1, n = 1.49 for example:

$$\frac{dP}{dt}=-\alpha\,\{4.526\,P_B+2\,P_K\}=O,\ so\ P_K=-2.263\,P_B. \tag{48}$$

Let m = 3, n = 1.49 for example:

$$\frac{dP}{dt}=-\alpha\,\{6.526\,P_B+4\,P_K\}=O,\ so\ P_K=-1.632\,P_B. \tag{49}$$

Let m = 5, n = 1.49 for example:

$$\frac{dP}{dt}=-\alpha\,\{8.526\,P_B+6\,P_K)=O,\ so\ P_K=-1.421\,P_B. \tag{50}$$

Let m = 7, n = 1.49 for example:

$$\frac{dP}{dt}=-\alpha\,(10.526\,P_B+8\,P_K)=O,\ so\ P_K=-1.316\,P_B. \tag{51}$$

The first example, for m = 1, will be recognized as equivalent to the simple focus athermalization calculated earlier, and indeed for this case, the power P is not dependent upon h, and represents negligible spherical aberration. The successive terms show increasing dependence of P upon h, and represent successive orders of spherical aberration. In each order m, a combination of $P = P_B + P_K$ can always be found to add to a desired zonal power h, with a ratio of P_K and P_B such that P for that order m is athermalized to the degree desired. Note that the ratio P_K/P_B will approach -1 for large m, so that athermalization may require increasingly large opposing contributions of P_K and P_B.

The foregoing derivation shows explicitly that a solution will exist for the athermalization not merely of focal power, but also for each and every individual order of spherical aberration. An optical designer will recognize that the derivation will still apply, with numerical modifications, for other object and image distances and for lenses that are not thin and not weak and not flat.

Another embodiment for the invention using PMMA can reduce the dependence of spherical aberration and back focal length on temperature. A composite lens 130 as shown in Figure 10 has kinoforms 132 and 134 formed on both sides of the bulk refractive portion of the structure. Spherical aberration is corrected as described before by introducing a third power relationship for the second kinoform. Here, the equation expressing the relationship for simultaneously correcting for back focal length and spherical aberration is then:

$$P_{K1} + P_{K2} + P_B = k \tag{52}$$

So that:

$$\frac{(P_{K1} + P_{K2})}{P_B} = -M \tag{53}$$

The lenses of the invention fully incorporate passive means for reducing the temperature dependency of optical characteristics that vary with the geometry and refractive index of the lens. The lenses are nevertheless made of a single material.

Figure 10 can also illustrate an example of an athermalized Germanium hybrid lens. Here lens 130 has the convex refractive surface 132. Kinoform 134 overlies a concave base surface 133. This lens is a thermal to one part in 10^8 at 10.6 microns.

According to some embodiments of the invention, the lenses or systems do not fully athermalize the temperature dependence of the focal length or other characteristics but reduce them as required for particular applications. That is, the degree of athermalization is not complete, but the kinoform or kinoforms have powers which still compensate for the temperature induced changes in focal length or other characteristics of the lenses or devices.

According to different embodiments of the invention, various materials are used for the temperature-dependence reducing or athermalizing lenses. In each case, the kinoform accomplishes its athermalizing or temperature- dependence reduction end by exhibiting a power which is a substantial proportion of the bulk power. For example, the kinoform-bulk ratio for athermalized lenses may vary from .15 to 10.0. Preferably the ratio is between .5 and 2.0. In plastic lenses, the kinoform power has a sign opposite to the bulk power in the a thermal case.

The following table shows examples of different bulk materials used for a variety of single piece refractive/ kinoform lens combinations for correcting chromatic aberrations (achromat) and the temperature dependence of the focal power:

		ACHROMAT		ATHERMAT	
Combination	Total Power	Bulk	Kino	Bulk	Kino
BK7/KINO	1	0.9489	0.0511	1.3684	-0.3684
PMMA/KINO	1	0.9433	0.0567	-0.8769	1.8769
GERM/KINO	1	0.9974	0.0026	0.0843	0.9157
KRS5/KINO	1	0.9851	0.149	-1.0240	2.0240

KRS 5 is a Thalium-Bromide Thalium-Iodide material.
GERM is Germanium
BK7 is spectacle glass

The above shows that in absolute terms, for any material, the kinoform in the 1 athermalized hybrid lens contributes at least 4 times as much as the kinoform in the achromatized lens. In general, in the athermalized lens, the kinoform power contribution is at least 20% in absolute values, and in the achromatized lens the kinoform power contribution is less than 15%. In a plastic athermalized lens the kinoform power is either larger than the bulk power or of opposite sign.

The invention furnishes passively athermalized lenses and optical devices. It also provides lenses and devices whose variations in response to temperature changes are reduced passively to any desired degree.

While embodiments of the invention have been described in detail, it will be evident to those skilled in the art that the invention may be embodied otherwise.

The various embodiments illustrated may be fabricated using the techniques shown and described in an article by P.P. Clark and C. Londono, "Production of kinoforms by single point diamond machining", Optics News, December (1989) which is incorporated here in by reference.

One example of an inventive lens fabricated using diamond turning techniques is shown in Fig. 11 where it is shown at 200. Lens 200, fabricated of PMMA, comprises a front negative aspheric surface 202 and a rear aspheric base surface 204 on which is formed kinoform 206, itself a collection of grooves of varying size which are designated generally by 208. As before, surfaces 202 and 204 and the intervening material provide the refractive power for lens 200.

Lens 200 has an effective focal length of 50 mm at 0° C, an entrance pupil diameter of 12.5 mm and a relative

aperture of f/4. Fig. 12 is a perspective photograph of it from the vantage point of looking up from the lower right quadrant (referenced to viewing the front surface face on) through the front surface with kinoform 206 appearing as imaged through front surface 202. Kinoform 206 has 1072 grooves which vary in radial width with the widest being close to the optical axis and the narrowest located at or near the largest clear diameter.

The base curvature of front surface 202 is 0.029043498801, and it has aspheric coefficeints of: A = 0.19491434E-05 and B = 0.27304523E-08. Base surface 204 is spherical and has a curvature of 0.004306653067.

The radial position of grooves 208 along with radial width, given by in general by: $y_{n+1} - y_n$ appears in the following table where the last column also gives the width in waves based on a wavelength of 632 nm.

ZONE	Y (mm)	SIZE (mm)	SIZE (waves)
1	0.190.752	0.190752	301.44
2	0.269764	0.079012	124.86
3	0.330393	0.060628	95.81
4	0.381505	0.051112	80.77
5	0.426536	0.045031	71.16
6	0.467247	0.040711	64.34
7	0.504685	0.037438	59.16
8	0.539532	0.034847	55.07
9	0.572260	0.032729	51.72
10	0.603216	0.030956	48.92
-	-	-	-
-	-	-	-
-	-	-	-
1062	6.223288	--	--
1063	6.226224	0.002936	4.64
1064	6.229158	0.002935	4.64
1065	6.232091	0.002933	4.64
1066	6.235023	0.002932	4.63
1067	6.237954	0.002930	4.63
1068	6.240883	0.002929	4.63
1069	6.243811	0.002928	4.63
1070	6.246737	0.002926	4.62
1071	6.249662	0.002925	4.62
1072	6.252586	0.002924	4.62

The following table gives the variation in back focal length and power for lens 200 and includes for comparison the performance of a reference lens of the equivalent purely refractive power.

FIRST-ORDER PROPERTIES			
			REFERENCE
	T = 0°	T = 20°	T = 40°
EFL	49.695	50.000	50.308
BFL	46.756	47.052	47.351
t	4.993	5.000	5.007
RMS WFE	.002/.0036	.002/.037	.002/.037

(continued)

FIRST-ORDER PROPERTIES			
REFERENCE			
	T = 0°	T = 20°	T = 40°
max defocus, waves	3.590	-0.111	-3.810
HYBRID			
	T = 0°	T = 20°	T = 40°
EFL	49.993	50.000	50.007
BFL	52.374	52.372	52.374
t	4.993	5.000	5.007
RMS WFE	.001/.036	.002/.034	.002/.034
max defocus, waves	.0.040	-0.045	-0.049

Finally, Fig. 13 shows is the graphical equivalent of the data of the foregoing table showing that the focal length of the inventive lens remains substantially constant over the displayed temperature range. The departure in the variation of focal length from a completely flat curve is believed to be because of slight differences between actual and assumed values for the actual material variation of index with temperature.

Claims

1. A lens (10) comprising a bulk portion having a first (14) and a second (16) surface, at least one of the surfaces (14, 16) of the bulk portion being curved, said bulk portion providing a refractive power, and at least one of the surfaces (16) of the bulk portion being provided with a kinoform (20), said kinoform providing kinoform power, the sum of said refractive power and said kinoform power being equal to the total optical power of said lens, characterized in that the lens (10) is formed by a single material and in that the curved surface or surfaces of the bulk portion and the kinoform (20) are structured and arranged such that, with changes in temperature, the temperature induced changes in the refractive power and in the kinoform power have different signs, so that at least the total power and focal length (42) change with temperature in a predetermined way.

2. The lens as claimed in claim 1, wherein the ratio of said kinoform power to said refractive power is negative and substantially constant over the temperature change.

3. The lens as claimed in claim 1, wherein said kinoform power is sufficient to athermalize the lens.

4. The lens as claimed in claim 1, wherein said refractive surface is substantially spherical.

5. The lens as claimed in claim 1, wherein said refractive surface is substantially cylindrical (70).

6. The lens as claimed in claim 1, wherein one of the surfaces has an aspheric component (86).

7. The lens as claimed in claims 1 to 6, wherein the grooves (82) of said kinoform (84) have aspheric profiles which change with temperature to compensate for changes in spherical aberration of said lens (80) with temperature.

8. The lens as claimed in claims 1 to 7, wherein said at least one curved bulk surface (86) is aspheric and changes with temperature to compensate for changes in spherical aberration of said lens (80) with temperature.

9. An optical device comprising a lens (52) having a bulk portion with a first (56) and a second (58) surface, at least one of the surfaces (56, 58) of the bulk portion being curved, said bulk portion providing a refractive power, and at least one of the surfaces (58) of the bulk portion being provided with a kinoform (60), said kinoform (60) providing kinoform power, the sum of said refractive power and said kinoform power being equal to the total optical power of said lens (52), the device further comprising a spacer (50) for spacing said lens from an optical target, said spacer exhibiting changes in dimensions in response to changes in temperature, characterized in that the lens (52) is formed by a single material and in that the curved surface or surfaces (56,

58) of the bulk portion and the kinoform (60) are structured and arranged such that, with changes in temperature, the temperature induced changes in the refractive power and in the kinoform power have different signs, so that the device responds to the variations in temperature in both the spacer (50) and at least the total power and focal length in a predetermined way.

10. The optical device as claimed in claim 9, wherein said kinoform (60) has a power sufficient to compensate at least partially for the variations in the spacer (50) and in at least one of total power, focal length and spherical aberration in response to the changes in temperature.

11. The optical device as claimed in claim 9, wherein said at least one curved bulk surface has aspheric components and said kinoform (60) has aspheric profiles, and the kinoform has sufficient aspheric kinoform power to offset changes in spherical aberration of said device at the optical target in response to changes in the temperature at at least one predetermined wavelength.

12. A method of manufacturing an optical lens according to any one of claims 1 to 11, comprising the steps of:
forming from a transparent material a lens (10, 30, 52, 70, 80, 200) comprising a bulk portion having a pair of refractive surfaces (14, 16, 56, 58, 202, 204) at least one of the surfaces being curved so that at least total power and focal length (42, L) of said lens bulk portion vary in response to changes in temperature; forming a kinoform (20, 33, 60, 206) integral with and made of the same material as said bulk portion on one of said surfaces (14, 16, 56, 58, 202, 204), said kinoform having a power sufficient to vary at least total power and focal length (42, L) of said lens in response to changes in temperature in a direction opposite to the direction which the changes in temperature impose on said bulk portion (10, 30, 52, 70, 80, 200) at at least one predetermined wavelength.

13. The method as claimed in claim 12, characterized by the additional step of mounting said lens (52) in a mount (50), wherein the step of forming the kinoform (60) includes forming the kinoform (60) with enough power to also compensate for at least a portion of temperature-induced changes in the mount (50).

Patentansprüche

1. Linse (10), welche einen massiven Teil aufweist, der eine erste (14) und eine zweite (16) Oberfläche besitzt, wobei wenigstens eine der Oberflächen (14, 16) des massiven Teils gekrümmt ist und der massive Teil eine Brechkraft liefert und wobei wenigstens eine der Oberflächen (16) des massiven Teils mit einem Kinoform (20) versehen ist, welches eine Kinform-Brechkraft liefert, wobei die Summe der Brechkraft und der Kinoform-Brechkraft gleich der optischen Gesamt-Brechkraft der Linse ist,
dadurch gekennzeichnet, daß die Linse (10) aus einem einzigen Material besteht und daß die gekrümmte Oberfläche oder die Oberflächen des massiven Teils und des Kinoform (20) derart strukturiert und angeordnet sind, daß bei Temperaturänderungen die durch die Temperatur eingeführten Änderungen der Brechkraft und der Kinoform-Brechkraft unterschiedliche Vorzeichen derart besitzen, daß sich wenigstens die Gesamt-Brechkraft und die Brennweite (42) mit der Temperatur auf vorbestimmte Weise ändern.

2. Linse nach Anspruch 1, bei welcher das Verhältnis von Kinoform-Brechkraft zur Brechkraft des massiven Teils negativ und im wesentlichen konstant über den Temperaturbereich ist.

3. Linse nach Anspruch 1, bei welcher die Kinoform-Brechkraft ausreicht, um die Linse athermisch zu machen.

4. Linse nach Anspruch 1, bei welcher die brechende Oberfläche im wesentlichen sphärisch ist.

5. Linse nach Anspruch 1, bei welcher die brechende Oberfläche im wesentlichen zylindrisch (70) ist.

6. Linse nach Anspruch 1, bei welcher eine der Oberflächen eine asphärische Komponente (86) aufweist.

7. Linse nach den Ansprüchen 1 bis 6, bei welcher die Nuten (82) des Kinoform (84) asphärische Profile besitzen, die sich mit der Temperatur derart ändern, daß temperaturbedingte Änderungen der sphärischen Aberration der Linse (80) kompensiert werden.

8. Linse nach den Ansprüchen 1 bis 7, bei welcher die wenigstens eine gekrümmte Oberfläche (86) des massiven Teils asphärisch ist und sich mit der Temperatur derart ändert, daß durch die Temperatur eingeführte Änderungen der sphärischen Aberration der Linse (80) kompensiert werden.

9. Optische Vorrichtung mit einer Linse (52), die einen massiven Teil mit einer ersten (56) und einer zweiten (58) Oberfläche besitzt, wobei wenigstens eine der Oberflächen (56, 58) des massiven Teils gekrümmt ist, und wobei der massive Teil eine Brechkraft liefert und wenigstens eine der Oberflächen (58) des massiven Teils mit einem Kinoform (60) versehen ist, das eine Kinoform-Brechkraft liefert, wobei die Summe der Brechkraft des massiven Teils und des Kinoform gleich ist der optischen Gesamt-Brechkraft der Linse (52) und wobei die Vorrichtung außerdem einen Abstandshalter (50) aufweist, um die Linse gegenüber einem optischen Ziel zu distanzieren und der Abstandshalter Dimensionsänderungen gemäß Temperaturänderungen unterworfen ist,
dadurch gekennzeichnet, daß die Linse (52) aus einem einzigen Material hergestellt ist und daß die gekrümmte Oberfläche oder die gekrümmten Oberflächen (56, 58) des massiven Teils und des Kinoform (60) derart konstruiert und angeordnet sind, daß bei Temperaturänderungen die durch die Temperatur eingeführten Änderungen der Brechkraft und der Kinoform-Brechkraft unterschiedliche Vorzeichen derart besitzen, daß die Vorrichtung auf Temperaturänderungen sowohl im Abstandshalter (50) und wenigstens der Gesamt-Brechkraft und der Brennweite in vorbestimmter Weise anspricht.

10. Optische Vorrichtung nach Anspruch 9, bei welcher das Kinoform (60) eine Brechkraft aufweist, die ausreicht, um wenigstens teilweise Veränderungen des Abstandshalters (50) und wenigstens der Gesamt-Brechkraft oder der Brennweite oder der sphärischen Aberration gemäß Temperaturänderungen zu kompensieren.

11. Optische Vorrichtung nach Anspruch 9, bei welcher wenigstens eine gekrümmte Oberfläche des massiven Teils eine asphärische Komponente besitzt und das Kinoform (60) asphärische Profile hat, wobei das Kinoform eine genügende asphärische Kinoform-Brechkraft besitzt, um Änderungen in der sphärischen Aberration der Vorrichtung am optischen Ziel gemäß Änderungen in der Temperatur bei wenigstens einer vorbestimmten Wellenlänge zu kompensieren.

12. Verfahren zur Herstellung einer optischen Linse gemäß einem der Ansprüche 1 bis 11 mit den folgenden Schritten: es wird aus einem transparenten Material eine Linse (10, 30, 52, 70, 80, 200) hergestellt, die einen massiven Teil mit zwei Brechoberflächen (14, 16, 56, 58, 202, 204) aufweist, wobei wenigstens eine der Oberflächen derart gekrümmt ist, daß wenigstens die Gesamtbrechkraft und die Brennweite (42, L) des massiven Teils der Linse sich gemäß Temperaturänderungen verändern; es wird ein Kinoform (20, 33, 60, 206) integral mit dem massiven Teil aus dem gleichen Material auf einer der Oberflächen (14, 16, 56, 58, 202, 204) ausgeformt, wobei das Kinoform eine Brechkraft aufweist, die ausreicht, um wenigstens die Gesamt-Brechkraft und die Brennweite (42, L) der Linse gemäß Temperaturänderungen in einer Richtung entgegengesetzt zur Richtung zu verändern, in der sich die Temperaturänderungen auf den massiven Teil (10, 30, 52, 70, 80, 200) bei wenigstens einer vorbestimmten Wellenlänge auswirken.

13. Verfahren nach Anspruch 12,
gekennzeichnet durch den zusätzlichen Schritt der Montierung der Linse (52) in einer Fassung (50), wobei der Schritt der Formung des Kinoforms (60) eine derartige Formung des Kinoform (60) bewirkt, daß dieses eine ausreichende Brechkraft besitzt, um wenigstens einen Teil der durch Temperatur eingeführten Änderungen der Fassung (50) zu kompensieren.

Revendications

1. Lentille (10) comprenant une partie massive comportant des première (14) et deuxième (16) surfaces, au moins une des surfaces (14, 16) de la partie massive étant courbe, ladite partie massive conférant un pouvoir réfringent, et au moins une (16) des surfaces de la partie massive étant pourvue d'une partie diffringente (20), ladite partie diffringente conférant un pouvoir diffringent , la somme dudit pouvoir réfringent et dudit pouvoir diffringent étant égale à la puissance optique totale de ladite lentille, caractérisée en ce que la lentille (10) est formée par une seule matière et en ce que la surface ou les surfaces courbes de la partie massive et de la partie diffringente (20) sont structurées et disposées de manière telle, qu'en présence de changements de température, les changements de température affectant le pouvoir réfringent et le pouvoir diffringent sont de signes différents, de sorte qu'au moins la puissance totale et la distance focale (42) varient avec la température d'une façon prédéterminée.

2. Lentille selon la revendication 1, dans laquelle le rapport dudit pouvoir diffringent à ladite puissance de réfraction est négatif et sensiblement constant sur l'intervalle de changement de température.

3. Lentille selon la revendication 1, dans lequel ladite puissance de diffraction est suffisante pour rendre la lentille insensible à la température.

4. Lentille selon la revendication 1, dans laquelle ladite surface réfringente est sensiblement sphérique.

5. Lentille selon la revendication 1, dans laquelle ladite surface réfringente est sensiblement cylindrique (70).

6. Lentille selon la revendication 1, dans laquelle une des surfaces présente une composante asphérique (86).

7. Lentille selon les revendications 1 à 6, dans laquelle les rainures (82) de ladite partie diffringente (84) ont des profiles asphériques qui varient avec la température pour compenser les variations d'aberration sphérique de ladite lentille (80 en fonction de la température.

8. Lentille selon les revendications 1 à 7, dans laquelle la surface courbe (86) de la partie massive, au nombre d'au moins une, est asphérique et varie avec la température pour compenser les variations d'aberration sphérique de ladite lentille (80) en fonction de la température.

9. Dispositif optique comprenant une lentille (52) comportant une partie massive munie de première (56) et deuxième (58) surfaces, au moins une des surfaces (56, 58) de la partie massive étant courbe, ladite partie massive conférant un pouvoir réfringent, et au moins une des surfaces (58) de la partie massive étant pourvue d'une partie diffringente (60), ladite partie diffringente (60) conférant un pouvoir diffringent, la somme dudit pouvoir réfringent et dudit pouvoir diffringent étant égale à la puissance optique totale de ladite lentille (52), le dispositif comprenant en outre un élément d'espacement (50) destiné à espacer ladite lentille d'une cible optique, ledit élément d'espacement accusant des variations de dimension en réponse aux changements de température,

caractérisé en ce que la lentille (52) est formée par une seule matière et en ce que la surface ou les surfaces courbes (56, 58) de la partie massive et de la partie diffringente (60) sont structurées et disposées de manière telle qu'en présence de changements de température, les changements de températures affectant ledit pouvoir réfringent et le pouvoir diffringent sont de signes différents, de sorte que le dispositif réagit aux variations de température affectant à la fois l'élément d'espacement (50) et au moins la puissance totale et la distance focale d'une façon prédéterminée.

10. Dispositif optique selon la revendication 9, dans lequel ladite partie diffringente (60) a une puissance suffisant pour compenser au moins partiellement les variations affectant l'élément d'espacement (50) et au moins la puissance totale, ou la longueur focale ou l'aberration sphérique en réponse aux changement de température.

11. Dispositif optique selon la revendication 9, dans lequel ladite surface courbe de la partie massive, au nombre d'au moins une, présente des composantes asphériques et ladite partie diffringente (60) comporte des profiles asphériques, et la partie diffringente possède un pouvoir diffringent asphérique suffisant pour contrecarrer les changements d'aberration sphérique dudit dispositif à l'endroit de la cible optique en réponse aux changements de température à au moins une longueur d'onde prédéterminée.

12. Procédé de fabrication de lentille optique selon l'une quelconque des revendications 1 à 11, comprenant les étapes consistant :

à former à partir d'une matière transparente une lentille (10, 30, 52, 70, 80, 200) comprenant une partie massive comportant une paire de surfaces réfringentes (14, 16, 56, 58, 202, 204), au moins une des surfaces étant courbée de manière qu'au moins la puissance totale et la longueur focale (42, L) de ladite partie massive de la lentille varie en réponse aux changements de température;
à former une partie diffringente (20, 33, 60, 206) faisant corps avec ladite partie massive sur une desdites surfaces (14, 16, 56, 58, 202, 204) et formée de la même matière que cette partie massive, ladite partie diffringente ayant un pouvoir suffisant pour faire varier au moins la puissance totale et la distance focale (42, L) de ladite lentille en réponse aux changements de température dans un sens opposé au sens que les changements de température imposent à ladite partie massive (10, 30, 52, 70, 80, 200), à au moins une longueur d'onde prédéterminée.

13. Procédé selon la revendication 12, caractérisé par l'étape supplémentaire de montage de ladite lentille (52) dans une monture (50), l'étape de formation de la partie diffringente (60) comprenant la formation de la partie diffringente (60) avec un pouvoir suffisant pour compenser au moins une partie des changements de température induits dans la monture (50).

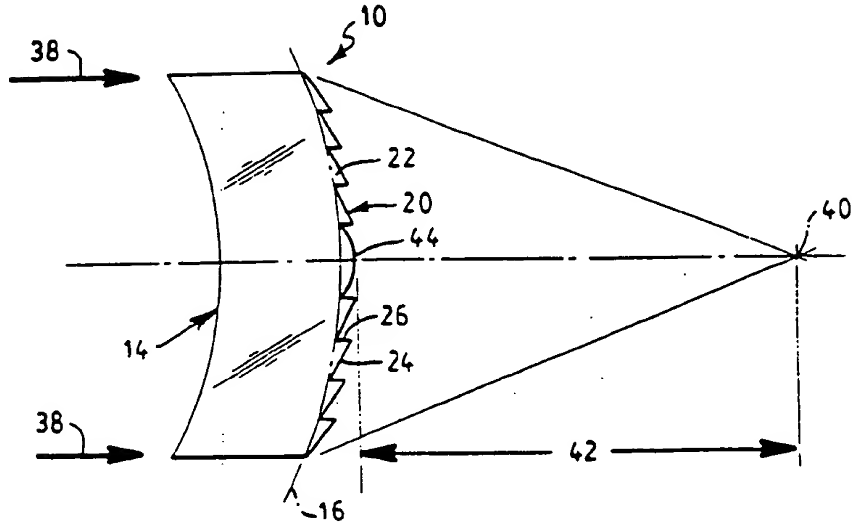

FIG. 1

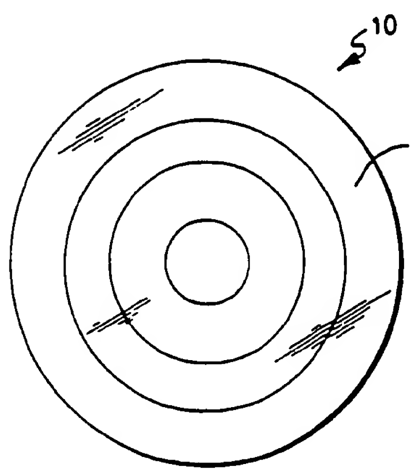

FIG. 2

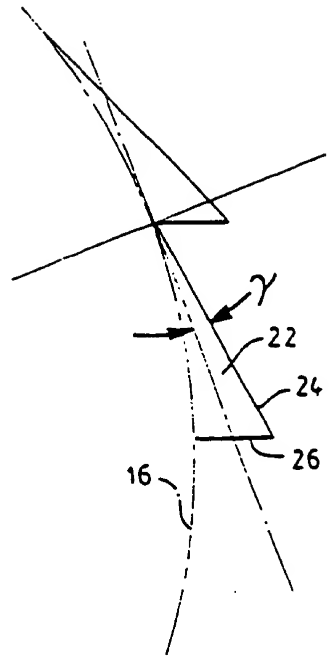

FIG. 3

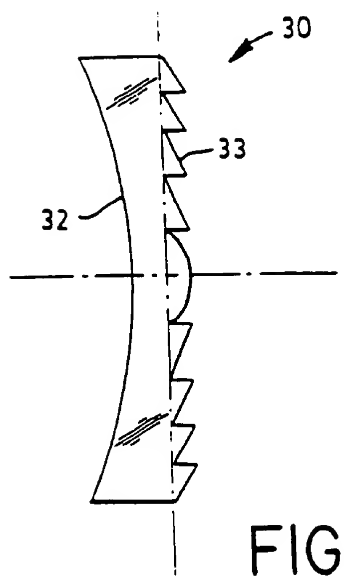

FIG. 4

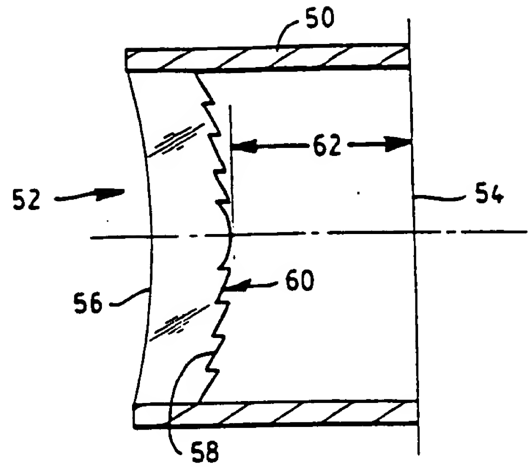

FIG. 5

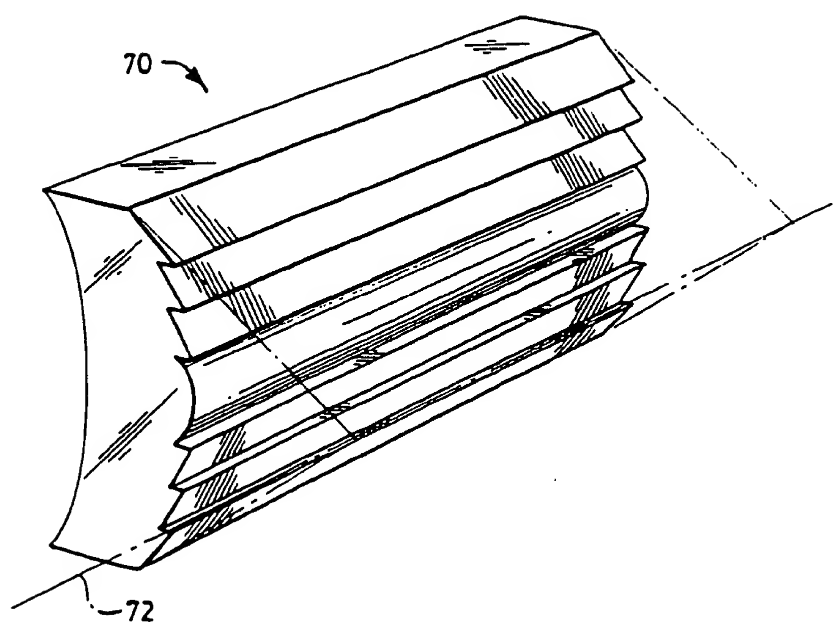

FIG. 6

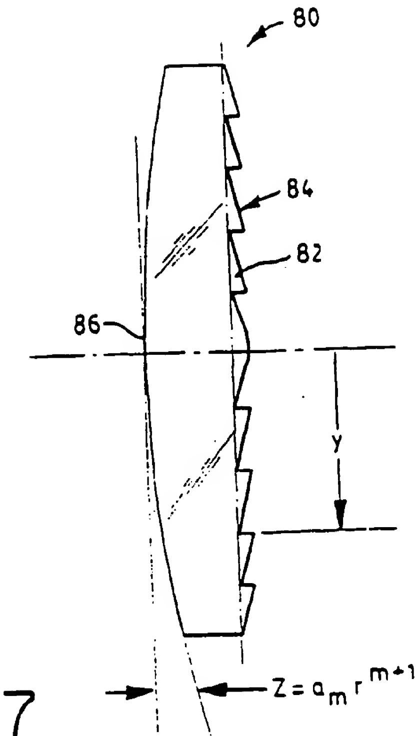

FIG.7

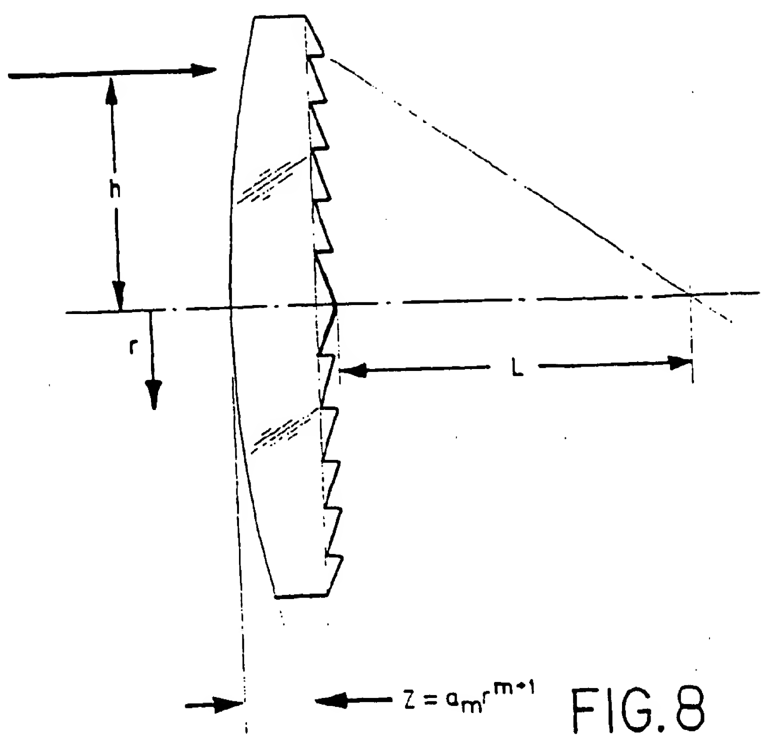

FIG.8

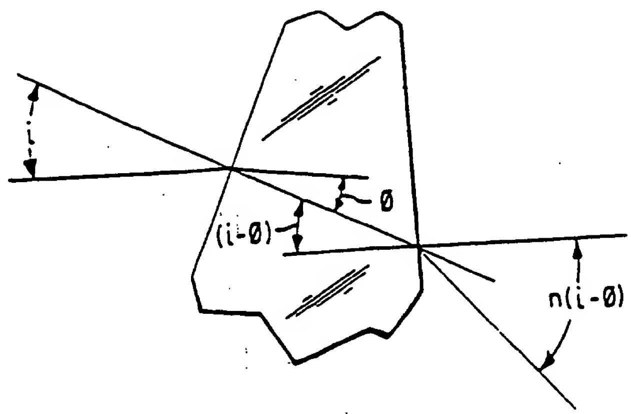

FIG.9

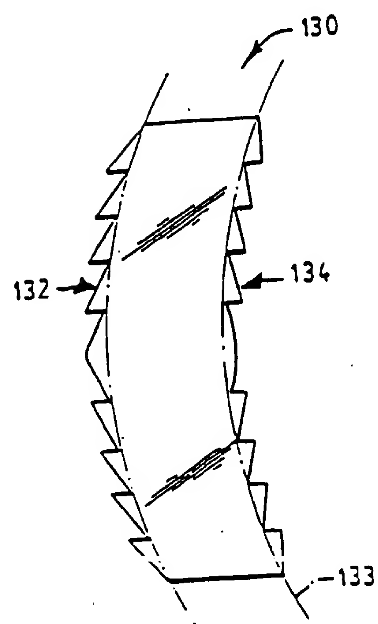

FIG. 10

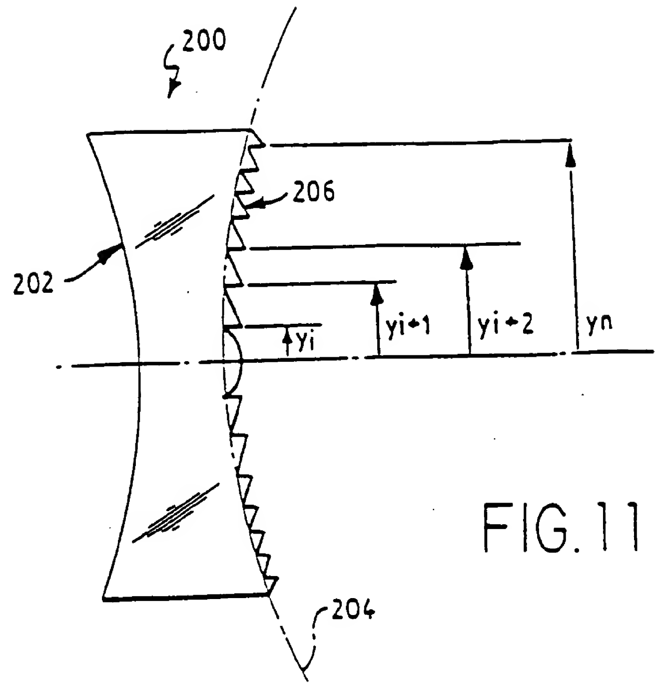

FIG. 11

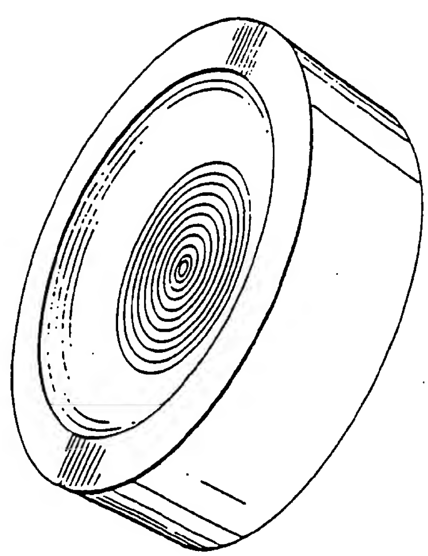

FIG.12

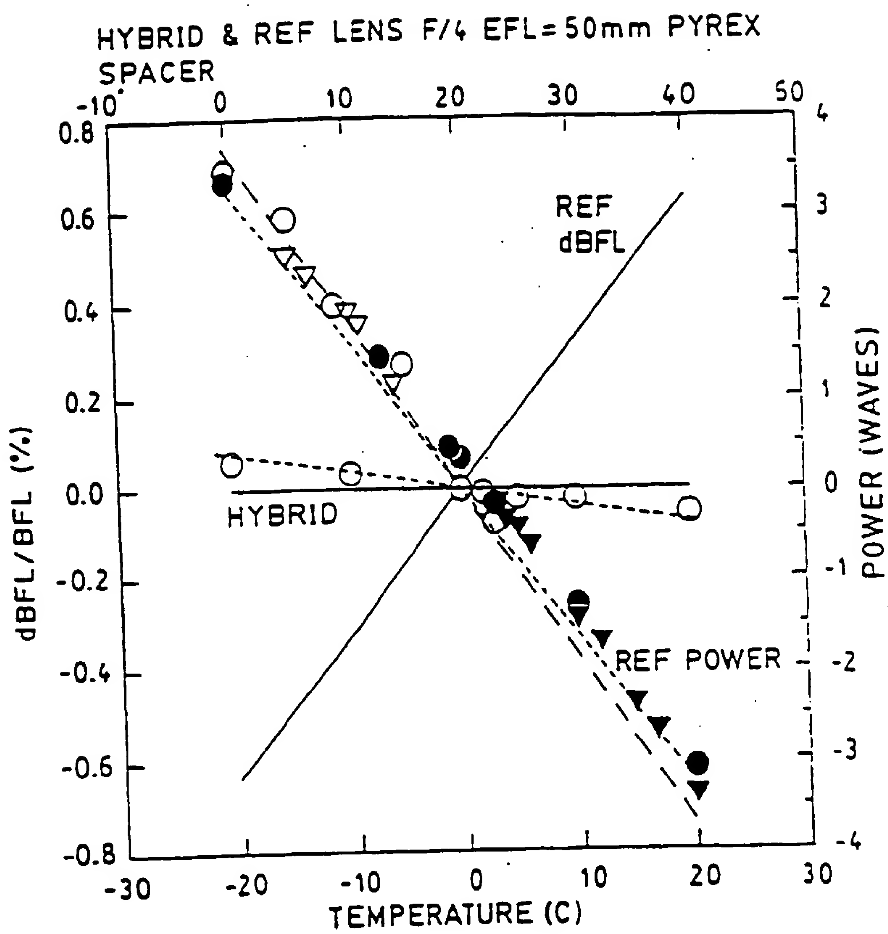
HYBRID & REF LENS F/4 EFL=50mm PYREX
SPACER
-10
0
10
20
30
40
50
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
4
3
2
1
0
-1
-2
-3
-4
REF
dBFL
HYBRID
REF POWER
dBFL/BFL (%)
POWER (WAVES)
-30
-20
-10
0
10
20
30
TEMPERATURE (C)

FIG. 13